

## THERMAL PROPERTIES OF HUMAN SKIN RELATED TO NONDESTRUCTIVE MEASUREMENT OF EPIDERMAL THICKNESS

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The thermal and physical properties of skin are reviewed briefly in the light of their relationship to skin functions and their influence on temperature measurement and related methodology. Thermal conductivity and epidermal thickness have a direct bearing on the majority of skin functions as these significantly affect heating rates, thermal pain thresholds, and blister formation, as will be seen from the experimental data. The accumulated data on both temperature and pain threshold are used to estimate epidermal thickness in the intact individual. The procedure to accomplish this end utilizes the measured thermal pain threshold, surface temperature, exposure time, and incident energy on a standardized skin site (volar surface of the forearm) to obtain conductivity values. These values are then used in a two-layer system heat flow equation to determine epidermal thickness in other skin sites (fingers) referred to the standard area.

Systematic exposures to various materials at high temperatures in contact-burn studies provide data for checking the reliability of this procedure by alternative computations and comparison with predicted tissue temperatures derived from earlier work. Certainly, blister formation and physical measurement of the excised epidermis would provide direct verification of the accuracy of the procedure but these measures have not been undertaken. It is quite possible that over a period of time verification data could be accumulated incidentally in the clinic where skin grafting procedures are carried out. For this purpose only relatively simple measurements of skin temperature and pain threshold, as described herein, would be required to be performed on skin graft donors to provide epidermal thickness measurements for comparison with direct measurements of excised skin immediately after removal.

The particular interest of our laboratory is in thermal hazards and protection therefrom. These hazards include fire, thermal radiation from nuclear detonations, and conduction burns from contact with hot materials. Therefore, we are concerned with precise evaluations of thermal and physical properties in order to devise protective measures which will prevent the skin from entering injurious energy-absorption time zones as depicted in Figure 1. Here is shown the tolerance time to pain and to blister end points for energy absorption rates up to about 1 cal/cm<sup>2</sup> sec as determined in earlier work [1]. This chart indicates the time at which pain and second-degree burn occur in the volar surface of the forearm on absorption of energy at the corresponding rates shown on the abscissa. Many factors affect the heat transfer rate: the mode of heating whether radiant, convective, or conductive; the thickness of the epidermal layer, which is primarily inert and insulative; and, in the instance of conductive heating, the properties of the material which contacts the skin.

### EXPERIMENTAL METHODS AND RESULTS

Our current concern is preclusion of pain or burn on contact with materials and furnishings of aircraft cockpits. The exact information requested

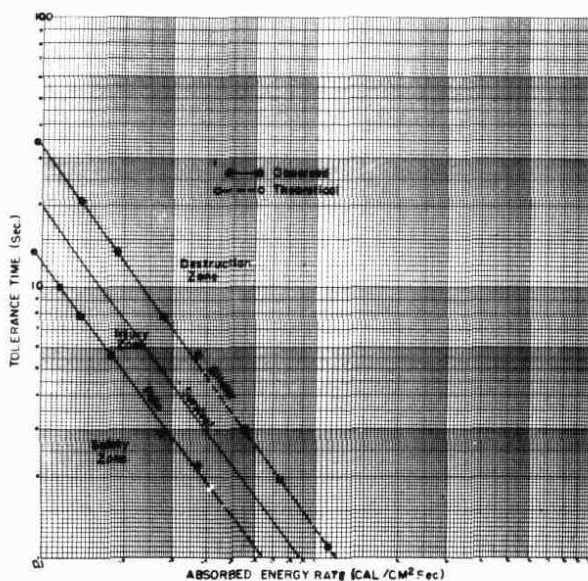


FIG. 1. Tolerance time to pain and burn in human skin on exposure to square-wave thermal irradiation.

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Abbreviation:

PT: pain threshold

by design engineers is a value for the highest permissible temperature for safe contact of skin with each material comprising or contained in a cockpit. Since most contacts are made with the fingers, where epidermal thickness is probably more variable than anywhere else on the body, this dimension becomes of utmost importance. An idea of its influence may be gleaned from the experimental data for skin in contact with materials at different temperature levels for exposure times to an end point of threshold pain. In this procedure the material is heated to a given temperature; the initial skin temperature, maintained at  $32.5 \pm 0.5^\circ\text{C}$ , is measured radiometrically just before contact with the heated material; the temperature of the material is measured at the same time; contact is made at time zero and maintained until pain threshold is reached; the interface temperature is recorded throughout by a fine wire thermocouple attached to the finger.

As seen in Figure 2, data on a single subject in contact with a single material yield a different curve for each of 3 fingers of the same hand because of the difference in the thickness of the epidermal layer. Earlier experiments have indicated that the effective depth of the pain receptors lies in the dermis at that level where a firing temperature of about  $43^\circ\text{C}$  occurs [1]. Increased thickness of the epidermis lengthens the heat transfer pathway to the receptor level, changes the total conductivity, and increases the time to pain perception. This effect is evident here and in Figure 3 where the data for 4 subjects using the right ring finger are shown. These subjects, although only 4 in all, represent a wide difference in epidermal thickness. Two are females, data curves to the left, with thinner epidermis than the 2 males. The latter illustrate the difference between a desk worker and a machinist-technician with heavily calloused fingers. At the longer pain threshold times there is little difference in the specimen temperature required to produce the end point, but at the shorter times, where the insulative properties of the epidermal layer exert the greatest effect, the difference in specimen temperature for the same pain threshold time in the subjects having the thinnest and the thickest epidermis is significant, in this particular instance  $30^\circ\text{C}$ . This very fact, however, provides a means of measuring epidermal thickness in intact skin.

For this purpose it is necessary to establish the pain threshold of all 4 subjects in a site in which the epidermis is uniformly thin. Experience has shown that the volar surface of the forearm represents such an area. In the present study, the pain threshold of each subject was measured in this area with a radiant energy source, a commercially available Dolorimeter in which the shutter was modified to provide a truly square-wave pulse over a small area (1.3 cm diameter). The radiant flux required to produce the pain threshold in 3 sec in all subjects was  $300 \pm 8\%$  mcal/cm<sup>2</sup> sec at an initial skin temperature of  $32.5^\circ\text{C}$ , measured radi-

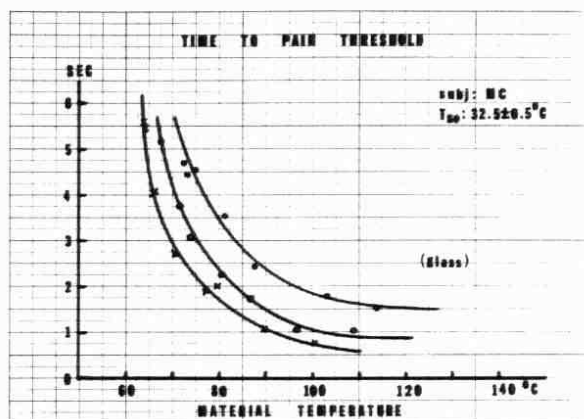


FIG. 2. Pain threshold times for 1 subject in contact with one material at different temperature levels. x = Ring finger; O = middle finger; ● = index finger.

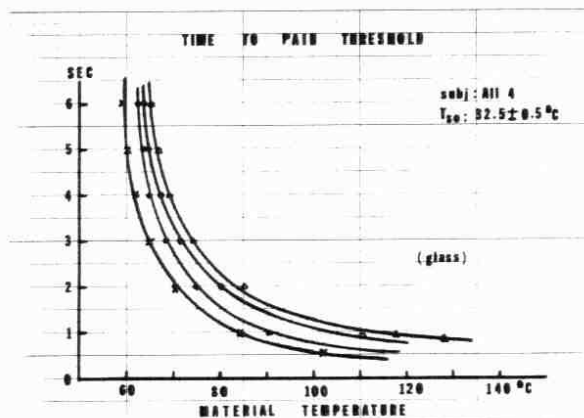


FIG. 3. Pain threshold times for 4 subjects in contact with one material at different temperature levels. Symbols for subjects: x = AS; ● = MC; O = JP; Δ = DZ.

ometrically. Such agreement confirms the uniformity of epidermal thickness in this area for all subjects as indicated in the earlier studies [1]. The latter also showed that the surface temperature at pain threshold in this area, at this heating rate, is about  $47^\circ\text{C}$ , and a value of about  $80 \mu$  for epidermal thickness is acceptable. Building upon these data, then, similar pain threshold measurements were made on each of 3 "test" fingers of each subject and the thermal inertia calculated from the relationship for surface heating:

$$k\rho c = \frac{4\alpha^2 Q^2 t}{\pi(\Delta T)^2}$$

where

- $k\rho c$  = thermal inertia (cal<sup>2</sup>/cm<sup>4</sup> sec °C<sup>2</sup>)
- $k$  = thermal conductivity (cal/cm sec °C)
- $\rho$  = density (gm/cm<sup>3</sup>)
- $c$  = specific heat (cal/gm)
- $\alpha$  = absorptivity
- $Q$  = irradiance (cal/cm<sup>2</sup> sec)
- $t$  = time (sec)
- $\Delta T$  = surface temperature rise,  $T_t - T_0$  (°C)
- $T_t$  = surface temperature at time  $t$
- $T_0$  = initial surface temperature

Since the product  $\rho c$  is approximately unity, this value for  $k\rho c$  may be taken as  $k$ , the surface conductivity. It is not exact because of the blackening agent on the skin surface. However, this layer is necessary to provide surface heat absorption and, being less than  $10\ \mu$  thick, should exert a relatively small overall effect. Then, using the equations of Griffith and Horton [2] for transient heat flow in a two-layer system (*Appendix*), the required data are obtained as follows: The conductivity value derived above is inserted as  $k_1$ , the conductivity of the outer layer in the equation for surface heating (Eq 2, *Appendix*) where  $U_0$  is the difference between pain threshold (PT) temperature,  $47^\circ\text{C}$ , and the initial skin surface temperature as measured. The equation is then solved for  $k_2$ , the conductivity of the dermis. Here the epidermal thickness is  $\alpha_1$ , the total thickness from surface to thermoreceptor level is  $x$ , and the dermal thickness to the receptor level ( $x - \alpha_1$ ) is  $\alpha_2$ . For the volar surface of the forearm  $\alpha_1$  is about  $80\ \mu$  and  $\alpha_2$  then is  $(x - 80\ \mu)$ . Similarly, the subscripts 1 and 2 denote properties of the epidermis and the dermis, respectively. The values so obtained,  $k_1$  and  $k_2$ , are inserted in the equation for  $U_2$ , (Eq 1, *Appendix*) the temperature rise at depth where  $U_2 = (43 - 32.5^\circ)$ , the difference between receptor level temperature at PT and the initial temperature, respectively. This equation is solved for  $x$ , the total depth from surface to receptor level and  $(x - 80\ \mu) = \text{depth of the receptors within the dermal layer}$ . Assuming now only that this depth is fairly uniform throughout the skin, finger pad PT data are used in the same series of calculations to arrive at  $\alpha_1$ , the epidermal thickness of each finger pad.

The first set of data so obtained is shown in the Table.

DISCUSSION AND CONCLUSION

At the present time these data must be considered to be preliminary and fragmentary, a first approach serving to illustrate the possibilities of the procedure, and open to discussion. For instance, the values of  $k$  appear to be high for epidermis alone ( $>1.0$  vs approx.  $0.7 \times 10^{-3}$  as noted

earlier [3] and corroborated in studies somewhat similar to the present [4]) but lower than the values found for whole skin at PT (approximately  $2.4 \times 10^{-3}$ ) using silicone rubber overlaid on skin as described in [5]. However, with further development of the heat transfer data now being gathered in the contact burn study, more definitive results are anticipated. Fewer assumptions will be necessary because the interface temperatures are being measured directly and the thermal properties of the materials in contact with the skin are known accurately. Thus, it will be possible to provide directly measured values for insertion in the appropriate two-layer equations. The ideal, of course, would be to obtain physical measurements of excised skin following PT determinations in the site before excision to compare with the calculated values. In a clinical situation where skin grafting is done routinely, such experimental procedures are really not farfetched and could be very rewarding to the interested investigator.

That our present experimental measurements are indeed quite accurate is attested by the successful prediction of contact burn time and temperature from the PT determinations described. For example, with aluminum as the contact material the PT parameters shown in Figure 4 were obtained on the back and the pad of the same finger.

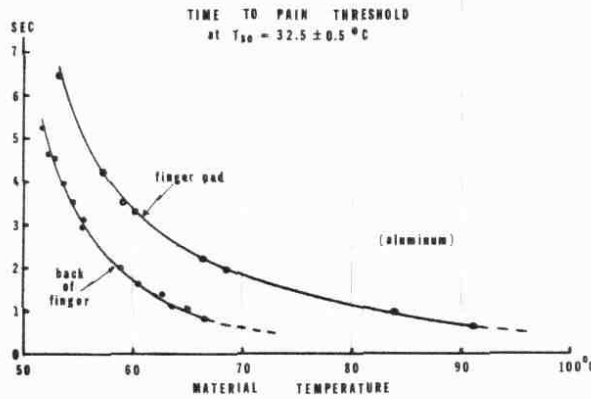


FIG. 4. Pain threshold times for 1 subject, pad and back of one finger, in contact with aluminum at different temperature levels.

TABLE. Epidermal thickness indicated by heat flow method

Subject	Thermal conductivity (volar surface of forearm) (cal/cm <sup>2</sup> sec °C) × 10 <sup>-3</sup>		Thickness (cm) = $\alpha$				
	$k_1$	$k_2$	Dermis	Epidermis ( $\alpha_1$ )			
			$\alpha_2$	$R_1$	$R_2$	$R_3$	$L_4$
AS	1.11	1.15	.0094	.0355	.0305	.0249	—
MC	1.38	1.65	.0101	.0433	.0319	.0259	—
JP	1.54	2.13	.0143	.0352	.0314	.0214	—
DZ	1.40	3.08	.0143	*—	** .0433	** .0416	** .0354

\* Out of range of Dolorimeter capability — either hand.

\*\* Left hand data. Right hand out of range.

$R_{1,2,3}$  = Right hand index, middle, and ring fingers, respectively.

$L_4$  = Left hand, little finger.



FIG. 5. Effect of contact with aluminum at predicted blister temperature. A at 0.2 sec = no burn; B at 0.45 sec = full blister.

From the data for the thin skin on the back of the finger, time to a minimal (threshold) blister was calculated on the basis of the relationship between pain and blister formation determined in earlier work [1]. From these data the time to virtually instantaneous threshold blister was predicted by extrapolation of the curve reciprocal time-to-blister vs specimen temperature to a contact time of 0.3 sec, just 0.1 sec over the reaction time of about 0.2 sec and the predicted temperature was 132°C. Figure 5 shows the result of exposures at this temperature: at 0.2 sec, no burn, only transient erythema occurred; at 0.45 sec a full blister formed 6 hr post exposure indicating overexposure for the desired end point but assuring for all practical purposes a threshold blister at the predicted time of 0.3 sec.

One final point of practical importance may be made, i.e., that measuring skin temperature by any probe contact method must be approached very carefully. Although it is well known and is implied in the present data, it is not immediately obvious that the thermal properties of the contact material have a profound effect on the final temperature of the skin, the quantity to be measured. On contact, equilibrium is achieved at some point intermediate between the two initial tempera-

tures, therefore, not the original temperature of either surface before contact [6,7].

This effect can be avoided only by selecting a probe material of exactly the same properties as the skin, a virtual impossibility, or preheating or precooling the probe until a null-point type of measurement results, a tedious and unwieldy system. It should be recognized, of course, that reproducible, relative values rather than absolute ones are often satisfactory for the clinician's purpose and in such instances a probe contact method is very convenient. Where absolute values and research order of accuracy are required, however, only a noncontact system will suffice.

## APPENDIX

### Equation 1- TEMPERATURE RISE AT DEPTH IN LAYER 2

$$U_2 = \frac{2H\lambda\sqrt{D_1}}{\gamma} \sum_{n=0}^{\infty} \left(-\frac{1}{\gamma}\right)^n \left\{ 2\sqrt{\frac{D_2}{\pi}} e^{-\left\{x-a\left[1-\sqrt{D_2/D_1}(2n+1)\right]\right\}^2/4D_2t} - \left[x-a\left[1-\sqrt{D_2/D_1}(2n+1)\right]\right] \left(1-\operatorname{erf} \frac{x-a\left[1-\sqrt{D_2/D_1}(2n+1)\right]}{2\sqrt{D_2t}}\right) \right\}$$

where

subscript 1 refers to top layer 1, subscript 2 refers to base layer 2  
and U = Temperature rise

H = Heat flux perpendicular to surface

X = Total thickness from surface to point of temperature rise measurement

a = Thickness of layer 1

D = Thermal diffusivity =  $k/S$

k = Thermal conductivity

S = Volume specific heat (density x specific heat)

$$\gamma = \frac{k_2 S_2 + \sqrt{k_1 S_1 k_2 S_2}}{k_2 S_2 - \sqrt{k_1 S_1 k_2 S_2}}$$

$$\lambda = (k_2\sqrt{D_1} - k_1\sqrt{D_2})^{-1}$$

### Equation 2- TEMPERATURE RISE AT SURFACE

$$U_0 = \frac{H}{k_1} \left[ 2\sqrt{\frac{D_1}{\pi}} \sum_{n=0}^{\infty} \left(-\frac{1}{\gamma}\right)^n \left\{ \sqrt{\frac{D_1}{\pi}} e^{-a^2 \frac{(n+1)^2}{D_1 t}} - a(n+1) \left(1-\operatorname{erf} \frac{a(n+1)}{\sqrt{D_1 t}}\right) \right\} \right]$$

### Equation 3- TEMPERATURE RISE AT INTERFACE

$$U_s = \frac{H}{k_1} \sum_{n=0}^{\infty} \left(-\frac{1}{\gamma}\right)^n \left(-\frac{1}{\gamma}\right) \left[ 2\sqrt{\frac{D_1}{\pi}} e^{-\left(\frac{a(2n+1)}{2\sqrt{D_1 t}}\right)^2} - a(2n+1) \left(1-\operatorname{erf} \frac{a(2n+1)}{2\sqrt{D_1 t}}\right) \right]$$

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